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Measurements and interpretation of registration of large number of neutrons generated in lead: the role of particle cascades

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Abstract. We register events with large number of neutrons at the ground level as well as in the underground laboratory. These neutrons are produced in secondary cosmic ray interactions with matter surrounding the neutron detectors. We used the set of helium–3 filled gas proportional counters and plastic scintillators. We performed a series of measurements in different experimental setups to determine a role of particle cascades in generation of large neutron multiplicities. With GEANT4 simulation of experimental setup we estimated number of neutrons produced in a single event which is required to explain our measurements.

1 Introduction

In cosmic ray studies, registration of neutrons in detector is often the indicator of hadronic component (e.g. neutron detectors in PAMELA in space, and (Chubenko et al., 2007; Erlykin , 2008; Stenkin et al., 2007, 2009) at ground EAS measurements). In underground low background laboratories neutrons constitute unwanted background. Most of these neutrons origin from radioactive processes, however there is a component due to high energy muon interaction. Part of this component are neutrons produced by large hadronic cascades generated in muon interaction in soil.

The process of simultaneous generation of large number of neutrons in the underground laboratory is still not well described (Cocconi et al., 1951; Ward et al., 2005). This is the main justification of presented studies.

The results might be important for deep underground and low background measurements e.g. search for dark matter or double-β decay. The neutron background and shielding against neutrons are very important in these studies.

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Standard approach is to measure the overall neutron background in low background laboratory, determine the neutron energy spectra and temporal variation. Then the low rate process detector shall be protected against external neutron background, determined as an average neutron flux (or energy spectrum).

The multiple neutron measurements might require different approach to neutron background protection in low background experiments (Malgin et al., 2008). These events are very rare and do not contribute significantly to the overall neutron background flux (Chubenko et al., 2008). However, the protection against thousands of neutrons produced in the same time might require a different approach, than protection against diffuse background.

This work is a continuation of our research conducted in previous years (Kasztelan et al., 2008). The main aim of presented here studies is to determine whether a large multiplicity of neutrons are created by the cascade of particles. We reconfigured our experimental setup by adding a second layer of lead and steel. We also placed the scintillator above and below the helium counters.

2 Detection methods: neutrons and cascades

We used the set of 14 ^{3}He proportional counters placed inside polyethylene blocks to detect neutrons. Additionally a lead or iron layer was placed above or under PE blocks (see Fig. 1).

We also used 1 m^2 scintillation detector to monitor charged particle cascades at the time of neutron registration. The scintillator was placed above or under the neutron detectors and lead/iron target. When it was placed on a top, then cascades originated in the ceiling and above were measured. When the scintillator was placed at the bottom, then cascades originated in the ceiling and also in the heavy target were measured.

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Fig. 1. Detector in the underground laboratory. Upper photo and from the top: helium counters in PE, 5 cm lead layer and scintillation counter. Bottom photo from the top: scintillation counter, helium counters in PE and 5 cm of lead.

All detectors were placed in the underground laboratory (below 13 m of soil), where we do not expect hadron cascades other than created in muon interactions.

Large number of particles in cascades might generate neutrons in 5 cm lead layer. This effect was observed. However, multiple neutron events without detecting cascades were measured, as well.

3 Lateral size

For several events it was possible to measure lateral size of multiple neutron events. We observed large number of neutrons in nearby helium counters, and none in most of remaining counters.

14 counters were connected to 7 FADC channels in pairs. Counters were placed inside PE blocks - 3 counters in one block - still 2 nearby counters were connected to one FADC, as shown in the Fig 2. Scintillation counter was connected to the 8^{th} channel of FADC. All FADC channels are clocked in the same way, and trigger came from any of neutron counters. We record 32 k of ADC‘s from all channels every 800ns for 8.5 ms before the trigger and 17 ms after the trigger (total 25.6 ms). Situation presented in the Figs. 2 and 3 suggest that neutrons were emitted from compact volume of lead (under ^{3}He counters). As there is low amplitude signal in the scintillator, it is likely, that cascade might develop in lead, and first interaction took place under the scintillator level.

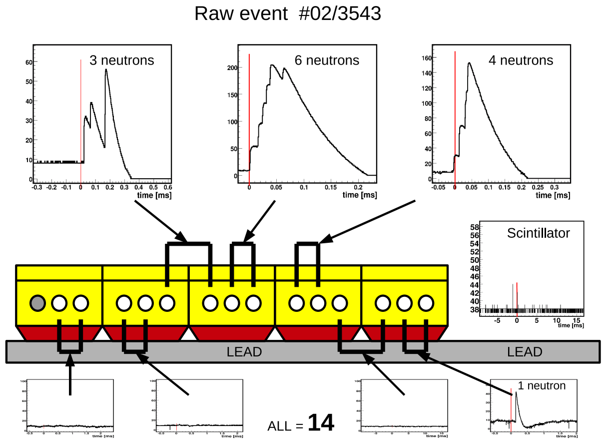

Fig. 2. An example of multiple neutron events with 14 neutrons and no significant signal in scintillation detector. Detectors are connected in pairs to FADC, as indicated. Scintillation counter was above neutron counters. Fig. 3 shows simulation for this event.

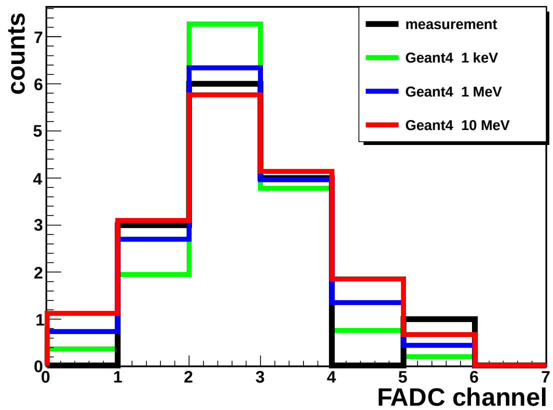

Fig. 3. Simulation of neutron lateral distribution shown in Fig. 2. We assumed that all neutrons were produced in one point in lead. Simulated distributions (different colours) were made for different emission energy of neutrons.

4 Efficiency of neutron registration

Helium proportional counters register charged products of neutron reaction n(^{3}He, ^{3}H)p. The cross section for this reaction is large for low energy neutrons and falls inversely proportionally to nonrelativistic neutron velocity, while emitted neutrons have large energies (up to 10 MeV). Therefore helium counters are placed in moderator (in this case poliethylene blocks) to slow down neutrons to thermal energies. Efficiency (see Fig. 4) and time of thermalisation depends on neutron energy and moderator geometry, and typically lasts tens of microseconds.

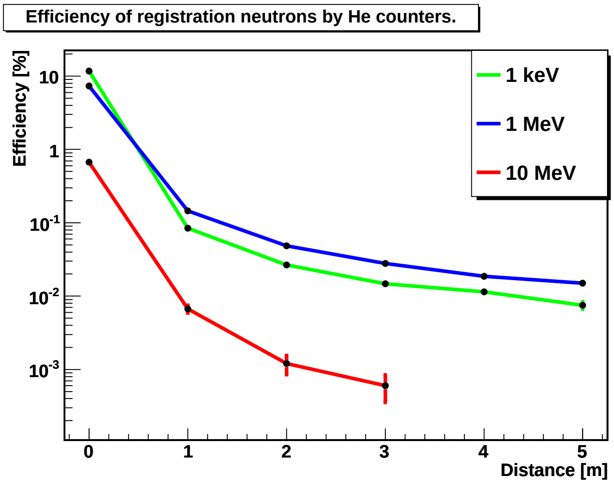

Fig. 4. Simulation of efficiency of neutron registration for our setup, using GEANT-4. It was assumed that neutrons were emitted (4π) in the center of lead layer (5 cm thick) at the indicated distance from the helium counter. Different lines represent neutron energies, as indicated. Figure shows probability of registration.

5 Multiple neutrons and cascades in the underground laboratory.

With scintillation counter below lead we can monitor whether multiple neutron events are correlated with cascades developed in the soil above the laboratory, in the polyehtylene or in lead under the helium counters (and above scintillator). From the calibration we know that a single muon produces a signal with amplitude with a peak distribution at the level of about 20 in ADC. The efficiency of 1 m^2 scintillation counter is 95%.

Here we show results from the setup with scintillator counter below lead and helium counters. The setup is shown in the upper photo of Fig. 1.

The total number of triggers was 126000 and effective time of measurements was 264.4 h. We collected 4543 events with 2 or more neutrons (see Fig. 5). Associated signals from scintillator were grouped in 4 classes: no signal, ADC signal smaller than 20 - “single charged particle”, small cascades with ADC between 20 and 200, and large cascades with ADC above 200 (or saturated).

In Fig. 6 number of neutrons were divided by the estimated number of charged particles in the scintillation counter. The main problem is to explain distributions for single or no (Fig. 5) charged particles in scintillation counter.

6 Neutron multiplicity distributions.

We have run several measurements in underground laboratory with different detector setups (see Table 1). Although the main reason was to see the role of cascades, we have

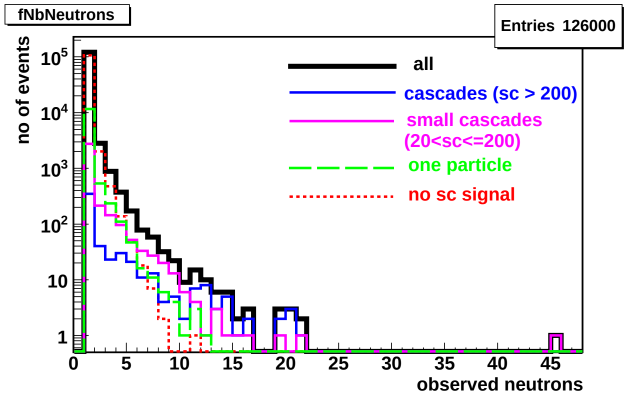

Fig. 5. Neutron multiplicity distribution (black). Distributions correlated with scintillator amplitude are indicated.

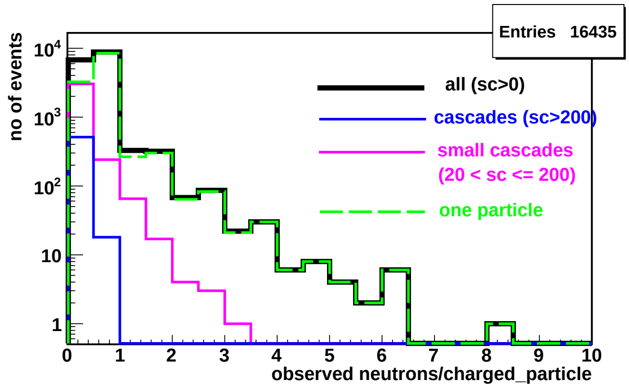

Fig. 6. Distribution of ratio of neutron number per single charged particle (ADC=20). Less than 1 neutron per charged particle was detected in case of large cascades (blue).

also studied dependence of neutron multiplicity distribution on the target material using lead or iron targets placed below helium proportional counters. Integral distribution (rate per hour) of observed multi–neutron events are presented in Fig. 7.

Example of coding: the setup shown in the upper photo Fig. 1 would have (^{3}He+PE)+Pb+Sc+Pb since from the top there are helium counters in PE, then lead layer, then scintillator, then large floor with 5 cm of lead.

The setup shown in the bottom photo of Fig. 1 would have code: Sc+(^{3}He+PE)+Pb+Pb.

The largest neutron multiplicity observed was 45. The statistics is too poor for definitive conclusion about the role of heavy target (lead) in multiple neutron production.

Moderator blocks (^{3}He+PE) used are made of polyethylene, cadmium and iron. However, the steel piece and closeby cadmium sheet were not present during measurements: Sc+(^{3}He+PE)+Pb+Pb, (^{3}He+PE)+Pb+Sc+Pb and (^{3}He+PE)+Fe+Sc+Pb.

Table 1. Information about measurements with different set-up. Colours refer to Fig. 7.

configuration from the top	colour	effective time	all events	multi–neutron events
Sc+(^{3}He+PE)+Pb+Pb	red	214.56 h	104979	3519
(^{3}He+PE)+Pb+Sc+Pb	black	264.44 h	125974	4543
Sc+(^{3}He+PE)+Pb	green	391.76 h	132905	4751
(^{3}He+PE)+Fe+Sc+Pb	magenta	120.35 h	41963	1168

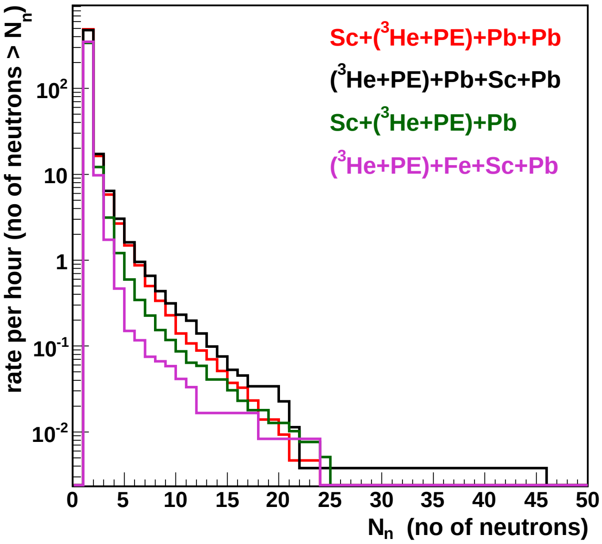

Fig. 7. Integral distribution of neutron multiplicity (see Sect. 6 for more details) Colours relate to labels. Labels indicate material distribution from the top (see Table 1). Sc – 1 m^2 scintillation counter 1 cm thick, with wooden base (1.8 cm), Pb – 5 cm thick lead layer, Fe - 8 cm thick iron layer, (^{3}He+PE) – helium proportional counter in polyethylene moderator.

7 Summary

The multiple neutron events were observed in the underground laboratory. The laboratory is deep enough to prevent EAS hadrons to penetrate. The most likely (however not experimentally proven, yet) mechanism of neutron generation is due to interactions of large cascades in lead. These cascades are originated in high energy muon interactions in surrounding soil, helium counter moderator or lead/iron target material.

However, we still register events with large number of neutrons with no signal in scintilator counter. As neutron detection efficiency (Fig. 5) is low, of the order of 1%, then $50-500$ times more neutrons need to be generated in detector vicinity, than measured in helium counters. For some events we would expect more than 1000 neutrons produced in cascade interaction in lead.

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